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Effect of methomyl and oxamyl soil applications on early control of nematodes and insects†

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Abstract

BACKGROUND: Methomyl is a widely used carbamate insecticide that has traditionally been applied as a foliar spray. More recently, methomyl has been labeled as a soil application via drip chemigation. Not much is known about the insecticidal and nematicidal potential of soil-applied methomyl. Methomyl soil applications were evaluated for their potential to control soil nematodes and foliar insect pests in a series of lab and greenhouse tests.

RESULTS: Methomyl showed rapid knockdown of *Meloidogyne incognita* (Kof. & White) Chitwood in aqueous assays, with EC_{50} and EC_{90} values that were similar to oxamyl and averaged 4.9 and 15.2 mg L^{-1}. In the greenhouse, soil applications of methomyl ranging from 0.56 to 4.0 kg ha^{-1} provided significant *M. incognita* control similar to oxamyl during early growth (up to 25 days after planting) of pea and bean. Higher application rates and split applications improved nematode control, but also increased the risk of phytotoxicity. Methomyl soil applications were highly effective on several insects including *Myzus persicae* (Sulzer), *Aphis gossypii* (Glover), *Frankliniella occidentalis* Perg. and *Spodoptera exigua* (Hübner). Methomyl was about 5–9-fold more potent on *M. persicae* and *A. gossypii* when applied via soil drench as opposed to foliar spray. Potency on *Bemisia tabaci* Genn., *S. exigua* and *Trichoplusia ni* Hübner was about the same with the two application methods.

CONCLUSION: Methomyl soil applications showed good potential for early control of various insect and nematode pests. Further testing is required to verify activity under field conditions.

Keywords: methomyl; *Meloidogyne incognita*; foliar insects; soil application

1 INTRODUCTION

Methomyl (Lannate®; DuPont, Wilmington, DE) is a systemic broad-spectrum carbamate insecticide that can be sprayed as a foliar material or applied to the soil. Methomyl has quick knockdown action and short to moderate residual activity.[1] Traditionally, methomyl has been mostly applied as a foliar spray, but recently soil applications have become more common. There are many benefits associated with soil as opposed to foliar applications, such as reduced risk of exposure to applicators and lower impact on above-ground beneficial insects, as has been shown with another carbamate, oxamyl.[2] Most data on methomyl efficacy are for foliar applications, but several reports have indicated good activity of soil-applied methomyl against aphids, leaf miners, thrips and mites.[1,3–5] Recently, the US EPA granted registration for use of methomyl as drip chemigation in onions for thrips control.[6]

The intrinsic nematicidal activity of methomyl was recognized when it was first introduced by DuPont in 1968. At that time, methomyl was marketed primarily as an insecticide. The focus was on foliar sprays as the preferred application method, which was not an effective method to control soil nematodes. Also, many superior nematicides were available at that time or were about to enter the market (carbamates such as aldicarb and oxamyl, organophosphates such as fenamiphos and several fumigant nematicides including methyl bromide, 1,3-dichloropropene and metam). Consequently, the nematicidal potential of methomyl was largely ignored. Recently, many of the former superior nematicides have come under increasing global regulatory pressure and are no longer available to growers. Methyl bromide, the nematicide standard for decades and a major ozone-depleting substance, has been pulled off the market.[7,8] Other fumigant-type nematicides, such as 1,3-dichloropropene and metam, as well as non-fumigant nematicides such as aldicarb, were not Annex I listed in the European Union (EU) and are facing a similar future to methyl bromide (Council Directive 91/414/EEC). It is in this context that methomyl could have some new potential as a soil nematicide.

Few and mostly old reports exist on the nematicidal activity of methomyl when applied to soil. McLeod[9] and Yassin[10] reported control of *Meloidogyne* spp. on tomato, and Cooper and Thomas[11] reported control of tobacco rattle virus (transmitted by *Trichodorus* spp. nematodes) on potato with soil-applied methomyl. Poor activity was noted against potato cyst nematode,[12,13] against

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beet cyst nematode[14] and against beneficial (entomopathogenic) nematodes.[15,16]

The following tests were carried out to evaluate the potential of methomyl soil applications for nematode and insect control.

2 MATERIALS AND METHODS

2.1 Materials

Methomyl 290 g L^{-1} LV (Lannate® LV) and oxamyl 240 g L^{-1} SL (Vydate® 24L) were synthesized by DuPont. The tested soil (74% sand, 21% silt, 5% clay; ~1% OM) was Matapeake sandy loam, which is a mixture of locally collected matapeake soil and sand. The aphids, whiteflies and thrips used in these tests originated from susceptible laboratory colonies (over 10 years old) routinely maintained at the Dupont Stine Haskell Research Center in Newark, Delaware. The lepidopteran species were purchased from Chesapeake Perl Laboratories, Newark, Delaware.

2.2 Incubation experiments

2.2.1 Nematode tests

Meloidogyne incognita (Kof. & White) Chitwood was originally isolated from cucumber in southern Delaware and maintained in the greenhouse on *Lycopersicon esculentum* (Mill.) cv. Bonny Best. Eggs were collected from ten-week-old plants with NaOCl.[17] Second-stage juveniles (J_2) were collected in hatching boxes, similar to the modified Baermann funnel method.[18] Only freshly hatched J_2 (24 h old) were used in the studies.

2.2.1.1 Lethal concentration (LC) assays (A) *Aqueous tests.* The nematicidal potential of methomyl compared with oxamyl against *M. incognita* was determined in seven separate aqueous tests. Methomyl and oxamyl treatments (20, 10, 5, 2, 1 and 0.4 μg AI mL^{-1}) were prepared in acetone + water (10 + 90 by volume), and 250 μL of solution was added to individual wells of a 96-well plate. Root-knot (RKN) nematode juveniles (J_2) were added to each well in 3 μL, containing between 15 and 30 J_2 (average 23) per well. Each treatment was replicated 8 times. Well plates were wrapped with parafilm, placed in plastic zip-lock bags and stored in aluminum foil pans covered with another pan to keep units dark. Units were kept at 22 °C. Nematode activity was evaluated after 48 h and 72 h (two tests only). Nematodes were considered dead when no movement could be observed at 40× magnification. Adjusted mortality was calculated using Schneider-Orelli's formula, whereby mortality was calculated as a percentage and adjusted to mortality in the control (solvent only) using the equation: % mortality adjusted = 100 × [(% mortality treated − mortality control)/(100 − mortality control)].[19] Adjusted mortality was used to calculate lethal concentrations required to kill 50% (LC_{50}) and 90% (LC_{90}) of nematodes.

(B) *Soil tests.* Similarly to the previous aqueous tests, the nematicidal potential of methomyl compared with oxamyl (LC_{50} and LC_{90} values) against *M. incognita* was also determined in four separate soil tests. Soil assays were done in small plastic containers filled with 10 g tested soil and a cucumber seed (cv. Straight Eight). Treatments were applied after cucumber seeds germinated (about 3 days). Methomyl and oxamyl treatments (250, 125, 62.5, 31.3, 16.1, 8, 4, 2 and 1 μg AI mL^{-1}) were prepared in acetone + water (10 + 90 by volume), and 330 μL of solution was added to each unit. Root-knot (RKN) nematode juveniles (J_2) were added in 330 μL, containing between 200 and 300 J_2 (average 250) per unit. Each treatment was replicated 3 times. Units were placed in the greenhouse at 25 °C and watered as needed. Nematode control was evaluated after 7 days by evaluating root galls on a scale of 0–10, where 0 = no galls, 1 = 0–10% of roots galled, ... and 10 = 90–100% of roots galled. Data are presented as percentage nematode control, where 100% means that no galls were found and 0% means that the amount of galls on the treated plants corresponds to that of the untreated control.

2.2.1.2 Soil efficacy bioassays All soil efficacy tests were done in the greenhouse in 10 or 14 cm square pots with non-pasteurized tested soil. Pots were filled with soil and prewet prior to seeding. Test plants were pea (*Pisum sativum* L. cv. Laxton Progess No. 9) and lima bean (*Phaseolus lunatus* L. cv. Henderson Bush). Two seeds were planted in each pot at a depth of 1.5 cm, and seedlings were thinned to one per pot after emergence. Peas were planted in 14 cm square pots and inoculated with 5000 root-knot nematode eggs (*M. incognita*) through four holes surrounding the seed. Beans were planted in 10 cm square pots and inoculated with 3000 root-knot nematode juveniles (J_2) through two holes surrounding the seed. Immediately after planting, pots were treated. Treatments were applied to each pot as a drench in water at 40 mL 100 cm^{-2} (equivalent to 4000 L ha^{-1}). Methomyl was applied at different rates ranging from 0.56 to 4.0 kg AI ha^{-1} and at application intervals starting at planting and up to 7 and 14 days after planting. Oxamyl soil drenches (0.56–2.24 kg AI ha^{-1}) were included as a comparison. In addition to the nematicidal tests, a series of phytotoxicity tests (two pea tests, one bean test) were carried out to evaluate the effect of methomyl drenches in the absence of nematodes. The same methodology, application rates and intervals were used as in the nematicidal tests. All phytotoxicity tests were done in 10 cm square pots.

Germination rate and emergence were recorded in all tests up to 14 days after seeding. Plant vigor ratings were done on a scale of 1–10, where 1 = poorest growth and 10 = best growth. Root-knot nematode infection was evaluated after 25 days by carefully removing roots and rating the roots for nematode galls on a scale of 0–10, where 0 = no galls, 1 = 0–10% of roots galled, ... and 10 = 90–100% of roots galled. Plant and root fresh weights were taken at the same time. Plant and root dry weights were taken after drying plants for 7 days at 25 °C.

All tests were conducted in the greenhouse (25 °C), except for one phytotoxicity test on pea that was done in the growth chamber (19 °C). Pots were watered as needed.

2.2.2 Insect tests

The following insects were evaluated for sensitivity to methomyl soil drench applications: green peach aphid, *Myzus persicae* (Sulzer) (Hemiptera: Aphididae), cotton aphid, *Aphis gossypii* (Glover) (Hemiptera: Aphididae), silverleaf whitefly, *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae), western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae), beet armyworm, *Spodoptera exigua* (Hübner) (Lepidoptera: Noctuidae), and cabbage looper, *Trichoplusia ni* (Hübner) (Lepidoptera: Noctuidae). A comparison of the potency of methomyl applied via foliar spray was also conducted on all of the above, except for *F. occidentalis*. All treatments had four replicates.

2.2.2.1 Chemical mixing and application Methomyl LV was mixed in water and diluted to the appropriate concentrations. Soil applications were done by drenching either 25 mL (6.25 × 6.25 cm pots) or 50 mL (10 × 10 cm pots) onto the surface of the soil. Foliar spray applications were done with a turntable sprayer at

10 rpm and 10 psi, and with an atomizing nozzle (Spraying Systems 12244SS).

2.2.2.2 Crops The following tested crops were grown in pots with the same soil mixture as for the above nematicide tests, except that soil was pasteurized: cotton, *Gossypium hirsutum* L. (cv. Deltapine 50, three-week-old plants, 6.25 × 6.25 cm pots), lima bean, *P. lunatus* (cv. Henderson, three-week-old plants, 6.25 × 6.25 cm pots), tomato, *L. esculentum* (cv. Orange Pixie, three-week-old plants, 10 × 10 cm pots), and cabbage, *Brassica oleracea capitata* L. (cv. Stonehead, five-week-old plants, 10 × 10 cm pots).

2.2.2.3 Aphis gossypii bioassay Aphids were reared in the laboratory on cotton seedlings and transferred to cotton test units by placing infested leaves onto the test plants and allowing the aphids to transfer overnight (aphids were of mixed age, about 90% nymphs). The next day, infested test units (having approximately 200 aphids plant^{-1}) were treated as described above at the following methomyl concentrations: 100, 50, 10, 2 and 0.4 μg AI mL^{-1} for the foliar-applied and 10, 2, 0.4, 0.08 and 0.016 μg AI mL^{-1} for the soil-applied treatments. Plants were then transferred to a growth chamber and held for 5 days at 28/24 °C day/night, 50% relative humidity (RH) and 16 : 8 h light : dark photoperiod. Plants were watered as needed from the top at the soil line. Test units were evaluated 5 days post-treatment for dead and live aphids. There were three replicates per concentration.

2.2.2.4 Myzus persicae bioassay The same procedure was followed as for *A. gossypii*, except that the aphids were reared in the laboratory on radish seedlings and transferred to tomato test units. Methomyl concentrations were 200, 100, 50, 10 and 2 μg AI mL^{-1} for the foliar-applied and 10, 5, 2.5, 1.25, 0.6 and 0.31 μg AI mL^{-1} for the soil-applied treatments.

2.2.2.5 Bemisia tabaci bioassay Cotton plants were trimmed to two true leaves per plant and introduced into cages where whitefly adults were allowed to lay eggs for approximately 24 h. After adults were removed, the underside of each leaf was inspected to make sure there were a minimum of 30 eggs. Insecticide applications were made as above when the second-instar nymphs settled (about 1 week later). Methomyl concentrations were 1000, 100 and 10 μg AI mL^{-1} for the foliar-applied and 1500, 1000, 500 and 100 μg AI mL^{-1} for the soil-applied treatments. Plants were moved to a growth chamber and held at 28/24 °C day/night temperature, 50% RH and 16 : 8 h light : dark photoperiod. Plants were watered as needed from the top at the soil line. Evaluations were made after 6 days by removing all leaves from each test plant and counting dead and live nymphs present on the underside of the leaf. There were three replicates per concentration.

2.2.2.6 Frankliniella occidentalis bioassay Cotton test units were sprayed as described above for *B. tabaci* and allowed to dry for 2 h after spraying. Methomyl was soil applied at concentrations of 80, 40, 20, 10, 5 and 2.5 μg AI mL^{-1}. A plastic cylinder enclosure with an opening at the top was placed around the plants. Adult thrips (about 2 days old) were collected from the laboratory culture and placed in a bazooka mixed with corn grits[20] dispensed in the test units at about 25 adults unit^{-1}. Lids were immediately applied to the top opening so thrips would not escape. The test units were transferred to a growth chamber with holding conditions set to 23/25 °C day/night, 70% RH and 16 : 8 h light : dark photoperiod. Plants were watered as needed from the bottom. The units were evaluated after 7 days, and live adults and larvae were counted. There were three replicates per concentration.

2.2.2.7 Spodoptera exigua and *Trichoplusia ni* bioassays Four cotton plants (one per pot) were treated as above and allowed to dry. Methomyl concentrations were 160, 80, 40, 20 and 10 AI mL^{-1} for *S. exigua* and 300, 100, 30, 10, 3 and 1 μg AI mL^{-1} for *T. ni*. Leaves were cut in approximately 6.25 cm^2 pieces and placed in 16-well plastic trays (Clear Pack, Franklin Park, IL) with cells containing approximately 2 mL agar (as a source of moisture). One three-day-old laboratory-reared beet armyworm or cabbage looper larva was placed in each cell, and the cells were covered with snap-on plastic lids (Brisar Delvco Packaging Services, Philadelphia, PA). Two 16-cell trays were used per concentration. Trays were held in a growth chamber at 25 °C, 75% RH and 16 : 8 h light : dark photoperiod, and larvae were evaluated for mortality 72 h post-infestation.

2.3 Data analysis

Data from the aqueous nematode tests and insect tests were analyzed by logit/probit dose response/mortality regression (Microsoft® Excel, Microsoft Corporation), and a lethal concentration (LC) was calculated. Data from the nematode soil tests were analyzed using analysis of variance or the general linear model procedures with JMP (SAS Institute, Inc., Cary, NC). Fisher's protected least significant difference (FLSD) test ($P \leq 0.05$) was used to separate treatments in tables. Differences between two means were analysed using single-degree-of-freedom contrasts.

3 RESULTS AND DISCUSSION

3.1 Nematodes

3.1.1 *Lethal concentration assays*

Mean nematode J_2 activity was high in the water controls (0% concentration), with values of >90% for *M. incognita* (RKN). Methomyl caused a high mortality (97%) of RKN J_2 at 20 mg AI L^{-1} (Fig. 1A). The calculated lethal concentrations required to kill 50% (LC_{50}) and 90% (LC_{90}) (after 48 h) for RKN were respectively 4.9 and 15.2 mg AI L^{-1} for methomyl as opposed to 4 and 11.5 mg AI L^{-1} for oxamyl (Fig. 1). After 72 h, LC_{50} and LC_{90} values (two tests only) averaged 3.6 and 9.8 mg AI L^{-1} for methomyl and 1.7 and 2.5 mg AI L^{-1} for oxamyl. Cucumber soil assays confirmed good nematicidal efficacy of methomyl, although the difference from oxamyl was greater than in water. LC_{50} and LC_{90} values were respectively 10.2 and 69.7 mg AI L^{-1} for methomyl as opposed to 2.8 and 12.0 mg AI L^{-1} for oxamyl (Fig. 1B).

Overall, the lethal concentration assays indicate that methomyl has very good nematicidal potential, only slightly less than that of oxamyl, a well-known and widely used nematicide. As is the case for all non-fumigant nematicides (carbamates and organophosphates), the biochemical effects at field rates can be reversed, and nematode recovery may occur if concentration and exposure time are too low.[21–23] Carbamates and organophosphates are therefore often called 'nematistatics' instead of nematicides. However, although technically, and under laboratory conditions, nematodes may recover, in real life they are probably too weak to locate a host root and would likely die of starvation.[24]

3.1.2 *Soil efficacy bioassays*

All application rates of methomyl (from 1.0 to 4.0 kg AI ha^{-1}) significantly ($P < 0.01$) reduced root-gall index on both pea and

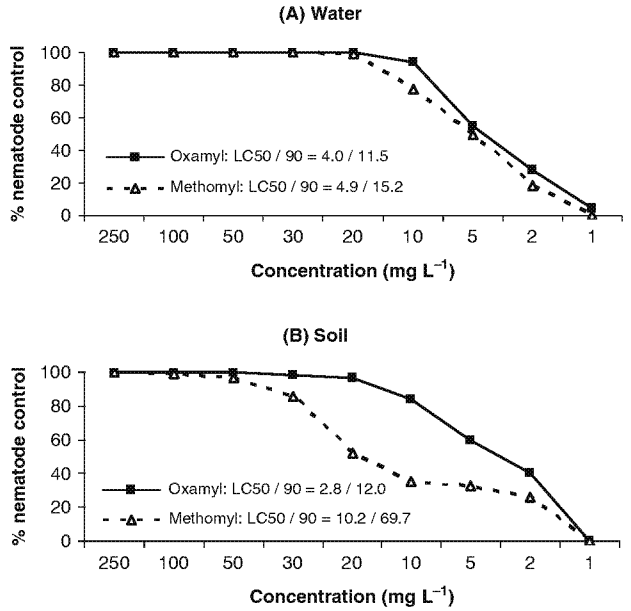

Figure 1. Nematode control (%) and effective concentrations (LC_{50} and LC_{90}) (mg L^{-1}) of methomyl and oxamyl against *Meloidogyne incognita* (RKN) juveniles (J_2) in water (A) and soil (B) assays (% control in water based on the ratio of dead and immobile nematodes to active and moving nematodes; in soil, based on reduction in root galls).

bean (Tables 1 and 2). This confirms the results from Yassin[10] who reported that 20 kg ha^{-1} of Lannate® 5 G (equivalent to 1 kg AI ha^{-1} of methomyl) showed good control of root-knot nematode [*Meloidogyne javanica* (Treub.) Chitwood] and higher yields in tomato fields in Sudan. McLeod[9] reported that, although Lannate® 90 WP at 7 mg L^{-1} did control *M. incognita* in tomato trays in the greenhouse, it did not control the same nematode at 4.5 kg AI ha^{-1} in field tomatoes. It is clear that differences in strength and type of formulations may affect nematode control. Lower-strength formulations require larger application volumes, resulting in more uniform soil distribution, which would benefit nematode control. Uniform soil coverage and distribution are important for any nematicide, but they are especially critical for non-fumigant (and 'nematistatic') materials such as methomyl.

The short residual activity of methomyl, with an average half-life in soil of 8.5 days,[1] would suggest that split applications might improve nematode control. Extra applications or higher rates, however, only slightly improved nematode control in the present tests, and only on pea, not on bean. Possibly, if nematode evaluations were done later than 25 days after planting, additional applications might have shown more benefit.

Higher application rates of methomyl (3 and 4 kg AI ha^{-1}) did increase the risk of phytotoxicity, which was especially visible on lima bean (Tables 3 and 4). Peas only showed slight leaf edge burn at higher rates, and only on older leaves. Symptoms on lima bean ranged from stunting, burning and leaf puckering to leaf necrosis on margins and spotty necrosis on the interior of the leaf and seem to indicate that lima bean is more sensitive to phytotoxicity than pea.

Reduced plant growth at the highest application rates was not evident in the two nematicidal tests, probably because nematode infection confounded phytotoxicity effects. In the absence of nematodes, lima bean plants showed reduced plant vigor and root weight when high at-plant application rates (1.2 kg AI ha^{-1}) were followed by one or two additional applications (1 kg AI ha^{-1}) (Table 4). High at-plant application rates without additional applications or low at-plant application rates with additional applications did not have a negative effect on bean growth.

Peas generally showed poor emergence at 25 °C (59% on average), probably owing to a combination of high temperature (peas do not tolerate high temperatures very well) and disease incidence, as non-pasteurized soil was used in all tests more closely to resemble field conditions. Therefore, phytotoxicity tests on peas (in the absence of nematodes) were evaluated at 25 °C and at 19 °C. No significant effect on plant growth was observed at 25 °C, but the test was compromised by poor and erratic emergence (66% on average). At 19 °C, plant emergence was much better (95% on average), and a slight numerical but no significant difference in plant and root weights was observed at the highest methomyl application rate of 4 kg AI ha^{-1} (Table 3). Lower application rates of methomyl (2 × 1 kg AI ha^{-1} at 0 and 7 days), on the other hand, improved plant vigor and root weight of pea by comparison with

Table 1. Effect of methomyl and oxamyl soil applications on root-knot nematode infection and plant growth of pea

Treatment	Rate (kg AI ha^{-1})	Timing[a]	Emergence (%)	Gall rating[b,c] (0–10)	Plant vigor[d] (1–10)	Plant (fresh g)	Root (fresh g)	Root (dry g)
Methomyl	2.0 (1.0 × 2)	0, 7 DAP	50 (±7)	1.8 (±0.36) b	7.3 (±0.59)	7.1 (±0.69)	2.04 (±0.37)	0.34 (±0.051)
Methomyl	3.0 (1.0 × 3)	0, 7, 14 DAP	63 (±3)	1.2 (±0.32) bc	7.2 (±0.53)	5.2 (±0.62)	0.89 (±0.33)	0.25 (±0.046)
Methomyl	3.0 (2.0 + 1.0)	0, 7 DAP	13 (±37)					
Methomyl	4.0 (2.0 + 1.0 × 2)	0, 7, 14 DAP	38 (±17)	0.7 (±0.42) bc	7.3 (±0.68)	5.5 (±0.80)	1.36 (±0.42)	0.31 (±0.059)
Methomyl	4.0 (3.0 + 1.0)	0, 7 DAP	88 (±23)	0.4 (±0.27) bc	6.9 (±0.45)	5.5 (±0.52)	1.59 (±0.28)	0.28 (±0.039)
Oxamyl	0.56	0 DAP	63 (±3)	1.0 (±0.36) bc	6.0 (±0.59)	4.4 (±0.69)	1.36 (±0.37)	0.17 (±0.051)
Oxamyl	1.12 (0.56 × 2)	0, 7 DAP	63 (±3)	0.0 (±0.36) c	7.0 (±0.59)	6.0 (±0.69)	1.61 (±0.37)	0.31 (±0.051)
Oxamyl	1.68 (0.56 × 3)	0, 7, 14 DAP	75 (±13)	0.0 (±0.36) c	7.5 (±0.59)	7.1 (±0.69)	1.76 (±0.37)	0.29 (±0.051)
Control with nematodes			75 (±13)	9.7 (±0.30) a	6.7 (±0.48)	4.3 (±0.56)	1.83 (±0.30)	0.25 (±0.041)
Control without nematodes			63 (±3)	0.0 (±0.32) c	7.8 (±0.53)	5.5 (±0.62)	0.89 (±0.33)	0.22 (±0.046)

[a] DAP = days after planting.
[b] Gall rating 0–10 scale: 0 = no galls, 1 = 0–10%, ... 10 = 90–100% of roots galled.
[c] Data are means of 5–10 replications. Means followed by the same letter are not different ($P = 0.05$) according to the LSD test.
[d] Plant vigor 1–10 scale with 10 = live and healthy plants and 1 = dead plants.

Table 2. Effect of methomyl and oxamyl soil applications on root-knot nematode infection and plant growth of bean

Treatment	Rate (kg AI ha^{-1})	Timing[a]	Emergence (%)	Gall rating[b,c] (0–10)	Plant vigor[d] (1–10)	Shoot (dry g)	Root (dry g)
Methomyl	1.0	At plant	100 (±5)	0.8 (±0.25) b	9.7 (±0.70)	1.79 (±0.17)	0.44 (±0.047)
Methomyl	2.0 (1.0 × 2)	0, 7 DAP	100 (±5)	0.5 (±0.25) b	9.7 (±0.70)	1.83 (±0.17)	0.38 (±0.047)
Methomyl	3.0 (1.0 × 3)	0, 7, 14 DAP	83 (±5)	1.2 (±0.25) b	9.6 (±0.76)	1.55 (±0.18)	0.38 (±0.052)
Methomyl	2.0	At plant	100 (±5)	0.8 (±0.30) b	6.7 (±0.70)	1.59 (±0.20)	0.36 (±0.058)
Methomyl	3.0 (2.0 + 1.0)	0, 7 DAP	83 (±5)	0.2 (±0.27) b	8.0 (±0.76)	1.39 (±0.18)	0.39 (±0.052)
Methomyl	4.0 (2.0 + 1.0 × 2)	0, 7, 14 DAP	83 (±5)	0.0 (±0.27) b	7.2 (±0.76)	1.02 (±0.18)	0.27 (±0.052)
Oxamyl	0.56	At plant	83 (±5)	0.6 (±0.27) b	7.2 (±0.76)	1.09 (±0.18)	0.31 (±0.052)
Oxamyl	1.12	At plant	100 (±5)	0.0 (±0.25) b	8.8 (±0.70)	1.49 (±0.17)	0.41 (±0.047)
Control with nematodes			83 (±5)	7.0 (±0.27) a	9.0 (±0.76)	1.84 (±0.18)	0.50 (±0.052)
Control without nematodes			100 (±5)	–	7.5 (±0.70)	0.93 (±0.17)	0.31 (±0.047)

[a] DAP = days after planting.
[b] Gall rating 0–10 scale: 0 = no galls, 1 = 0–10%, ... 10 = 90–100% of roots galled.
[c] Data are means of 5–10 replications. Means followed by the same letter are not different ($P = 0.05$) according to the LSD test.
[d] Plant vigor 1–10 scale with 10 = live and healthy plants and 1 = dead plants.

Table 3. Effect of methomyl soil applications on plant growth of pea[a]

Test	Rate (kg AI ha^{-1})	Timing[b]	Emergence (%)	Plant vigor[c] (1–10)	Plant height (cm)	Plant (fresh g)	Root (dry g)
Test 1, 27 °C	2.0 (1.0 × 2)	0, 7 DAP	50 (±17)	4.4 (±1.31)	7.1 (±1.68)	3.0 (±0.93)	0.16 (±0.084)
	3.0 (1.0 × 3)	0, 7, 14 DAP	80 (±13)	6.4 (±1.10)	9.1 (±1.27)	3.3 (±0.70)	0.27 (±0.064)
	3.0(2.0 + 1.0)	0, 7 DAP	70 (±6.7)	5.1 (±0.81)	7.0 (±0.97)	3.3 (±0.56)	0.20 (±0.051)
	4.0 (3.0 + 1.0)	0, 7 DAP	60 (±6.7)	4.9 (±1.10)	9.1 (±1.50)	3.1 (±0.83)	0.28 (±0.075)
	Control		70 (±3.3)	6.4 (±1.10)	9.6 (±1.50)	3.9 (±0.83)	0.33 (±0.075)
Test 2, 19 °C	2.0 (1.0 × 2)	0, 7 DAP	93 (±14.8)	9.0 (±0.26) a	7.3 (±0.60)	11.6 (±0.54) a	3.1 (±0.21) a
	3.0 (2.0 + 1.0)	0, 7 DAP	87 (±18.1)	7.8 (±0.26) b	6.9 (±0.60)	9.4 (±0.54) ab	2.2 (±0.21) b
	4.0 (3.0 + 1.0)	0, 7 DAP	100 (±0)	8.0 (±0.26) ab	6.3 (±0.60)	8.5 (±0.54) b	1.7 (±0.21) b
	Control		100 (±0)	7.8 (±0.26) b	6.2 (±0.60)	9.4 (±0.54) ab	2.0 (±0.21) b

[a] Data are means of 5–10 replications. Means followed by the same letter are not different ($P = 0.05$) according to the LSD test.
[b] DAP = days after planting.
[c] Plant vigor 1–10 scale with 10 = live and healthy plants and 1 = dead plants.

the control and higher application rates. As no nematodes were involved in this test, this seems to indicate a growth-promoting effect of methomyl. Growth-promoting effects as a function of the carbamate treatment itself interacting with the plant and irrespective of pest control effects have frequently been attributed to carbamates ('carbamate kick').[25,26]

Root-knot nematodes (*Meloidogyne* spp.) are important parasites of leguminous field crops such as pea and bean. Methomyl is commonly used as an insecticide in these crops, and may have additional potential as a nematicide when applied via soil.

3.2 Insects

LC_{50} and LC_{90} values for the various insects are shown in Table 5. Methomyl was about 5–9 times more potent on green peach aphid (*M. persicae*) and cotton aphid (*A. gossypii*) when applied via soil drench as compared with the foliar spray. Differences, however, were not statistically significant for *M. persicae* ($P > 0.05$). Potency on silverleaf whitefly (*B. tabaci*), beet armyworm (*S. exigua*) and cabbage looper (*T. ni*) was about the same with the two application methods. Methomyl was most potent on the two aphid species, on western flower thrips (*F. occidentalis*) and *S. exigua*. *T. ni* and *B. tabaci* had the highest LC_{50} and LC_{90} values, indicating lower potency on these two species. Toxicity of soil-applied methomyl to *A. gossypii* on potted cucumber was also reported by Binns.[3] The excellent efficacy of methomyl on thrips via soil drench that was seen in this study has been confirmed in field drip chemigation trials on onions (Baer C, DuPont, private communication). Methomyl soil application rates in these trials were 1 kg AI ha^{-1}. A label has been granted for this use in the United States (Dupont, EPA registration number 352–384). Control of *Thrips tabaci* Lind. on tobacco in Greece following methomyl drench was reported by Chatzivassiliou.[5] Thrips control in this trial was overall similar to imidacloprid, except 5 days post-treatment when methomyl gave better control. Efficacy against thrips needs to be verified in the field, and on larger plants, as this could affect systemic distribution of methomyl in the plant.

The high potency of methomyl on aphids, thrips and beet armyworm via soil drench confirms the good potential for methomyl to control these pests when applied via drip chemigation, shank injection or any other suitable method of delivery to the plant roots under field conditions.

Additional work is under way to determine the potential of methomyl on other pests and crops via root uptake. As in the nematicide tests, methomyl showed some phytotoxicity at the highest concentrations tested when applied to the soil (Table 6). Finding the appropriate rate that is efficacious and safe to the crop

Table 4. Effect of methomyl and oxamyl soil applications on plant growth of bean[a]

Treatment	Rate (kg AI ha^{-1})	Timing[b]	Emergence[c] (%)	Plant vigor[d] (1–10)	Plant (dry g)	Root (dry g)
Methomyl	0.56	0 DAP	80 (±6)	9.5 (±1.34) ab	1.20 (±0.23) ab	0.35 (±0.078) ab
Methomyl	1.56 (0.56 + 1.0)	0, 7 DAP	80 (±6)	8.3 (±0.95) ab	1.26 (±0.18) ab	0.26 (±0.066) b
Methomyl	2.56 (0.56 + 1.0 × 2)	0, 7, 14 DAP	80 (±4)	8.0 (±0.95) ab	1.25 (±0.18) ab	0.31 (±0.062) ab
Methomyl	1.12	0 DAP	80 (±6)	8.2 (±1.09) ab	1.51 (±0.20) ab	0.35 (±0.066) ab
Methomyl	2.12 (1.12 + 1.0)	0, 7 DAP	80 (±6)	4.4 (±1.01) b	0.66 (±0.20) b	0.20 (±0.066) b
Methomyl	3.12 (1.12 + 1.0 × 2)	0, 7, 14 DAP	60 (±14)	4.4 (±1.19) b	0.87 (±0.30) ab	0.22 (±0.101) b
Oxamyl	1.12 (0.56 × 2)	0, 7 DAP	80 (±6)	7.3 (±0.95) ab	1.48 (±0.18) ab	0.35 (±0.062) ab
Oxamyl	2.24 (1.12 × 2)	0, 7 DAP	70 (±4)	9.1 (±1.01) a	1.79 (±0.20) a	0.60 (±0.066) a
Control			70 (±16)	9.3 (±1.09) a	1.20 (±0.21) ab	0.36 (±0.071) ab

[a] Data are means of 5–10 replications. Means followed by the same letter are not different ($P = 0.05$) according to the LSD test.
[b] DAP = days after planting.
[c] Emergence (4 and 12 days after seeding).
[d] Plant vigor 1–10 scale with 10 = live and healthy plants and 1 = dead plants.

Table 5. Lethal concentrations (LCs) of foliar- and soil-applied methomyl for various insects and crops under laboratory conditions

Target	Crop	Application method	LC_{50}[a] (μg mL^{-1})	LCL–UCL[c] (μg mL^{-1})	LC_{90}[b] (μg mL^{-1})	LCL–UCL[c] (μg mL^{-1})
Myzus perscicae	Tomato	Foliar spray	9	3–26	44	19–11 459
		Soil drench	1	1–5	11	1–329
Aphis gossypii	Cotton	Foliar spray	25	15–36	54	38–99
		Soil drench	5	2–9	11	8–90
Bemisia tabaci	Cotton	Foliar spray	203	60–686	1589	115–18 326
		Soil drench	673	530–863	1119	870–2360
Frankliniella occidentalis	Beans	Soil drench	22	16–31	36	15–88
Spodoptera exigua	Tomato	Foliar spray	29	22–38	60	44–156
		Soil drench	18	12–23	30	23–148
Trichoplusia ni	Cabbage	Foliar spray	99	77–127	533	348–1084
		Soil drench	100	79–128	547	360–1089

[a] LC_{50} = lethal concentration to kill 50% of test organisms.
[b] LC_{90} = lethal concentration to kill 90% of test organisms.
[c] LCL = lower confidence limit; UCL = upper confidence limit.

Table 6. Plant damage (foliar edge burn) risk for foliar- and soil-applied methomyl on different crops under laboratory conditions

Crop	Crop age	Application	Rates (μg mL^{-1}) with plant damage
Cotton	4 weeks	Soil	1500, 1000, 500, 100
Cotton	4 weeks	Foliar	1500, 1000, 500
Cotton	3 weeks	Soil	1000, 100
Cotton	3 weeks	Foliar	1000, 100
Tomato	5 weeks	Soil	200, 100
Tomato	5 weeks	Foliar	200 no burn

will be an important consideration. Effective soil applications of methomyl should result in a safer use of the product because it will likely reduce undesirable effects on the environment and on non-target organisms.

4 CONCLUSION

Soil applications of methomyl showed similar or better efficacy against several insects by comparison with foliar sprays. In addition, soil applications provided good early control of root-knot nematodes (*Meloidogyne* spp.), similarly to oxamyl. The added benefit of nematode control is especially valuable, as regulatory and economic pressure has increasingly limited the number of nematicides available to growers at the moment. Methomyl could be a useful solution to these growers, who are in need of an economical option not only to control insects but also to control nematodes. Field tests are ongoing to evaluate the efficacy and crop safety of methomyl soil applications for different crops and against major insect and nematode parasites.

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